A Proposed Initiative for Capitalizing on the Parkfield, California, Earthquake Prediction (1986)

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PREFACE

In June 1985 a committee of the Board on Earth Sciences asked the National Research Council/National Academy of Sciences to bring to the attention of officials of the federal government the scientifically endorsed recent prediction of a moderate earthquake at Parkfield, California, between 1986 and 1993. This prediction offers a unique opportunity to improve our understanding of earthquakes and our future ability to predict them. An augmented experimental program at Parkfield is needed to document this high-probability event more completely, including the detection of premonitory phenomena.

Dr. Frank Press, President of the National Academy of Sciences, advised The Honorable Donald P. Hodel, Secretary of the Interior, of the unique opportunity and of the requirements for an improved field program; the Committee on Science, Engineering, and Public Policy arranged a special briefing for Dr. John McTague, the Acting Director of the Office of Science and Technology Policy of the White House; and several offices of the National Research Council arranged for a briefing of key Congressional staff at the Capitol of the United States.

This report contains the information that was presented to the governmental officials. It is intended to stimulate their interest, understanding, and enthusiasm for augmenting an experimental program. If successful, the Parkfield experiment will eventually translate into decreasing the vulnerability of people to earthquake hazards.

W. G. Ernst, Chairman
Board on Earth Sciences

1. THE PARKFIELD OPPORTUNITY: A SUMMARY

It has been predicted that a moderate-size earthquake will occur within the next few years at Parkfield, California. The prediction has been painstakingly reviewed and subsequently endorsed in 1984-1985 as scientifically valid by two highly qualified panels. Nowhere else in the world is a prediction in effect with a degree of confidence as high as that for Parkfield. Here, on a specific 25-kilometer segment of the San Andreas fault about half way between Los Angeles and San Francisco, studies during the past decade indicate a 95 percent probability that an earthquake of about magnitude 6 will occur between 1986 and 1993. There is an additional but lower probability that the actual ground rupture will be larger to the south than that predicted for the magnitude 6 earthquake, in which case more than 100,000 people could be affected. A significant scientific effort is currently underway, supported by both federal and California state funding, to monitor the Parkfield area with instruments, in the hope that it will be possible to predict the earthquake on a still shorter time scale--perhaps hours or days before the event. There are many scientific reasons for optimism that short-term precursors will in fact be observed and that a short-term prediction will be successful. The optimism is based primarily on remarkable and surprising similarities between 5 earthquakes that have occurred at this same location during the past 100 years.

However, because the current effort is centered on the placement of instruments at or near the ground surface, there is a high possibility that the next Parkfield earthquake will be predicted on an ad-hoc basis without yielding any real understanding of the physics of the fault-rupturing process and without giving us the fundamental scientific knowledge needed if we are to transfer this prediction capability to other faults in other geologic environments. To obtain the additional insight, it is clear that we must measure relevant physical parameters, such as stress, temperature, and fluid pore pressure, to depths several kilometers below the earth's surface, both before and after the earthquake. A truly unique opportunity exists at Parkfield to perform such critical experiments; but the sooner they commence, the greater the assurance that they will precede the earthquake.

The purpose of the proposed initiative, therefore, is to capitalize on the notable results to date that have succeeded in pinpointing the locality and approximate time of an impending significant earthquake, and to move beyond this to a new phase that will open up possibilities for understanding critical aspects of the physics of the earthquake process and how damaging earthquake ground motions are propagated in the close-in epicentral area. We propose to do this by installing a wide variety of monitoring instruments, mainly but not exclusively in deep boreholes. One cannot deny that there is a clear scientific risk that the experiment may not be successful, but if it is, the impact of these studies on worldwide earthquake-hazard reduction could be immediate and profound. In southern California alone, the application of transferable prediction results could affect the safety of several million people.

Among the specific recommendations made herein are the following:

o Drilling of 5 boreholes to depths of 5 km in and near the fault zone, for measuring shear stress, fluid pressure, seismic wave velocity, temperature, fluid chemistry, rock composition, permeability, density, magnetic susceptibility, and remnant magnetization.

o Emplacement of a profile of 1-2 km holes extending to a horizontal distance of 15 km from the fault, for measuring many of the same parameters but emphasizing stress and heat flow.

o Measurements of strain in more widely spaced 300-m boreholes out to distances of 30 km from the fault, tied to repeated high-precision geodetic surveys of the same region.

- Studies of crustal structure in the Parkfield area, utilizing seismic imaging techniques and based on data collected in densely spaced arrays of sensors both on the ground surface and in deep boreholes.
- Emplacement of an array of strong-motion seismometers with a spacing of about 100 m in an area close to the fault, for engineering studies of the nature of strong ground motion during the predicted earthquake.
- Carrying out of several engineering experiments to take advantage of the predicted earthquake: instrumentation of special structures such as small highway bridges and unreinforced masonry buildings; a special study of the behavior of buried pipelines where they cross active faults; and emplacement of instrumentation for intensive study of soil liquefaction in appropriate areas near Parkfield.

2. FACTS ABOUT PARKFIELD

Moderate-size earthquakes of about magnitude 6 have been seen to occur with remarkable similarities (so-called "characteristic" earthquakes) on the same segment of the San Andreas fault at Parkfield, California. Here, the fault-zone behavior is in transition, as ongoing aseismic "creep" to the north gives way southward to non-creeping "locked" behavior. The entire "locked" segment, which continues well into southern California, apparently ruptures only during infrequent great earthquakes of about magnitude 8, such as last occurred here in 1857 and will probably not occur again for about 200 years. Earthquakes of about magnitude 6 have occurred in the transition zone at Parkfield in 1881, 1901, 1922, 1934, and 1966, and at least the last three of these events are known to have been associated with southeastward rupture of the same 25-km-long segment of the fault. The segment is clearly bounded geometrically by a sharp 5° bend in the fault on the north and a 2-kilometer offset of the fault trace on the southern end. Further similarities between the most recent 1934 and 1966 events include foreshocks 17 minutes prior to the mainshocks, and very similar patterns of surface cracking. Based on this history, the next characteristic earthquake is expected in about 1988, as is illustrated in Figure 1. Figure 2 shows the location of the Parkfield segment in relation to other segments of the San Andreas fault system, which are themselves expected, with 30-year cumulative probabilities, to produce further significant earthquakes. The Parkfield segment, while producing smaller events than those characteristic of most other segments of the San Andreas fault, seems to produce them more often, with greater regularity, and with a greater probability of a characteristic event occurring within the next few years. Figure 3 gives the Parkfield recurrence model.

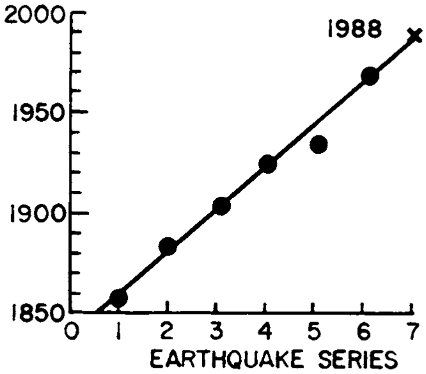

FIGURE 1: Series of earthquake sequences at Parkfield since 1850, taken from Bakun and Lindh, 1985. The line represents the linear regression of the time of the sequence obtained without the 1934 sequence. The anticipated time of the seventh (that is, the next) Parkfield sequence for the regression is January 1988.

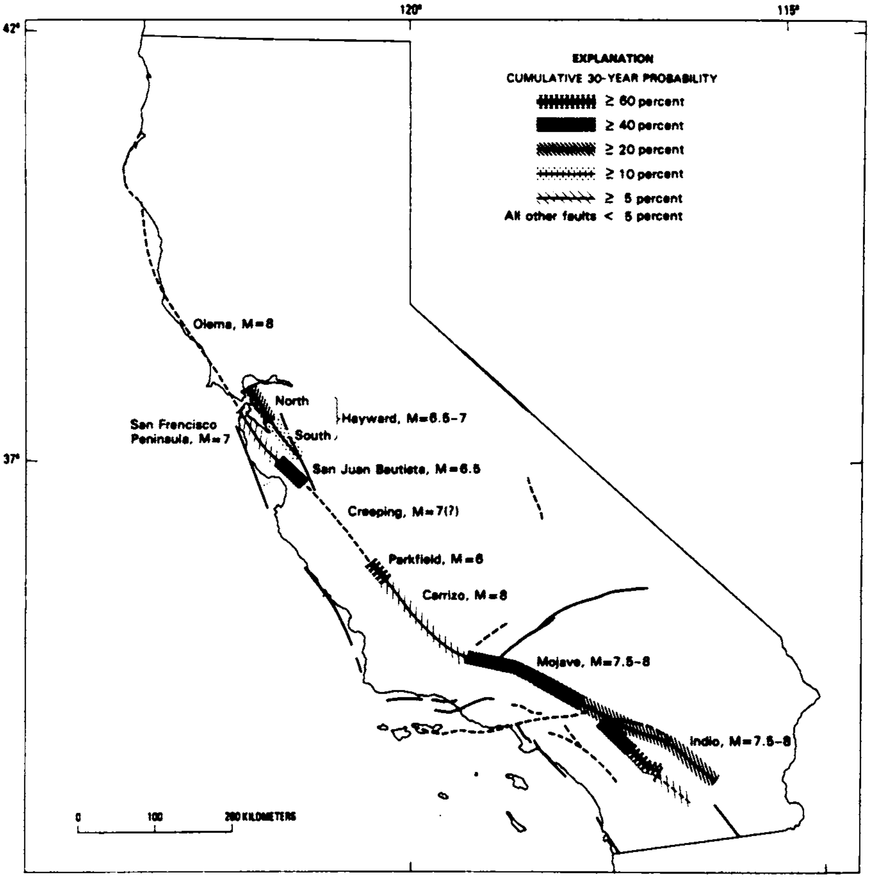

FIGURE 2: 30-year cumulative probabilities of occurrence of earthquakes along selected fault segments of the San Andreas fault system. Reconstructed from A.G. Lindh, "Preliminary Assessment of Long-Term Probabilities for Large Earthquakes Along Selected Fault Segments of the San Andreas Fault System in California" (U.S. Geological Survey Open-File Report 83-63), 1983. Figure 2 taken from Hanks, T. C., 1985.

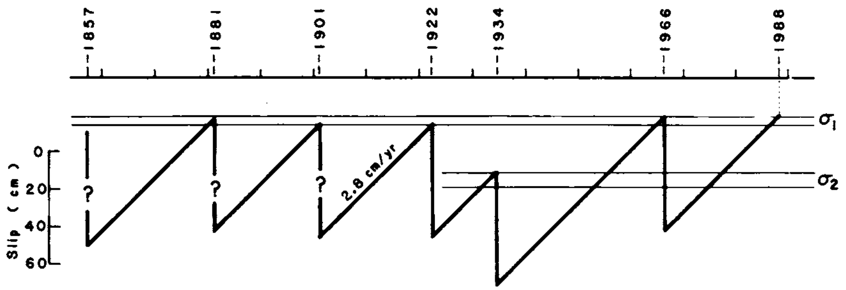

Figure 3: The Parkfield recurrence model. Most characteristic earthquakes occur at stress level σ_1; the 1934 shock occurred at σ_2. A constant loading rate of 2.8 cm per year and a coseismic slip of 60 cm for the Parkfield earthquake sequences in 1881, 1901, 1922, 1934, and 1966 are assumed. From Bakun and Lindh (1985).

Both the National Earthquake Prediction Evaluation Council and the California Earthquake Prediction Evaluation Council have reviewed the basis for the Parkfield prediction, as is discussed in the article by Kerr in the attached bibliography, and they concurred with the finding of a high probability (95 percent) that another magnitude 6 earthquake will occur at the Parkfield site in the 1986-1993 time interval. Confidence is sufficiently high in this expectation, and the timing and the magnitude of the predicted event are such, as to provide an unprecedented opportunity for deployment in the area of a dedicated system of monitoring instruments which, based upon knowledge gained to date in the prediction research program, constitutes the nation's prototype earthquake-prediction experiment.

Drawing on advances in prediction technology, the current Parkfield prediction experiment emphasizes intensive and precise monitoring of local earthquake activity at small magnitudes and of the small, continuous deformation of the earth's crust in the study region. A very sensitive local seismograph network, with several shallow borehole elements, is in operation along with a second low-gain network designed to record on-scale the expected magnitude 6 shock. Sensitive strain-measuring instruments have been emplaced downhole at shallow depths, and fault creep is being monitored in surface installations. A highly advanced two-color laser distance-measuring device measures a few times weekly a pattern of some 15 radial lines up to 6 kilometers long that span the fault zone, detecting length changes of less than 1 millimeter. Other measurements are being conducted by various government and university research scientists, as is discussed in articles in the attached bibliography. A high-speed microwave data link connects the site to the U.S. Geological Survey's research center in Menlo Park, some 300 kilometers to the north, where a 24-hour alert system notifies key personnel if anomalous signs are detected by the monitoring systems. Currently the link is being extended to appropriate California state agencies in Sacramento.

A major goal of the Parkfield prediction experiment is the issuance of a successful prediction of the expected earthquake on a short-term basis, i.e., days to hours in advance. This goal is a particularly important element in the California state participation in the experiment, and it has been responsible for increased attention being focused on the need for "hardening" the instrumentation and data-acquisition facilities, in order to avoid loss of the system's integrity, particularly during the strong shaking of the very event which the system is designed to predict. Even if the next Parkfield earthquake is not predicted on a short-term basis, however, analysis of the data in retrospect will have significant scientific rewards. Furthermore, it should be borne in mind that following the next Parkfield earthquake, perhaps the most promising place to predict another moderate-size earthquake will again be Parkfield. Such events occur here about every 22 years, and the opportunity to monitor the complete earthquake "cycle" at Parkfield with an experiment lasting only a couple of decades is unique. It should be noted that a recurrence period as short as 22 years is exceedingly unusual worldwide; recurrence intervals between significant earthquakes on major fault systems, including most other parts of the San Andreas fault, are typically on the order of hundreds or thousands of years.

3. STATE OF THE ART OF EARTHQUAKE PREDICTION

Scientists working in the field of earthquake prediction distinguish between long-term and short-term predictions. Long-term predictions, usually encompassing periods of years or tens of years, are based almost wholly on statistical extrapolations of past earthquake occurrences, as exemplified by the historic record of events repeated about every 22 years at Parkfield. Short-term predictions, on the other hand, attempt to recognize and utilize actual physical precursors to the impending event, such as foreshocks. Thus the scientific approaches are different, and our success during the past decade in long-term prediction has been exceedingly encouraging, as is exemplified by the articles by Sieh and by Sieh and Jahns in the attached bibliography, whereas success in short-term prediction remains more elusive. This has been in no small part due to the fact that until now it has not been possible to identify regions appropriate to focused short-term monitoring experiments. It is the long-term prediction of the Parkfield earthquake that has stimulated the intensive short-term prediction efforts in this area at this time.

3.1 PROGRESS IN LONG-TERM EARTHQUAKE PREDICTION

Significant progress has been made during the last decade toward the evaluation of long-term seismic hazard at specific locations and the recognition of increased potential for great earthquakes, at least for seismic zones along the boundaries of the lithospheric plates. The key to this progress has been the verification of the concept of the "seismic gap" as the site of a future significant earthquake. A seismic gap is a portion of a seismogenic zone, most easily recognized along a plate boundary, within which at least one strong earthquake is known to have occurred in the past, but where no such earthquake has taken place in a "long time." The determination of how long a time is required for a particular site to be called a gap is still largely empirical, but it is generally guided by data on the rates of relative plate motions across that section of the plate boundary, as well as by the documented intervals between past earthquakes, where such documentation is available. Seismic gaps have been identified with recurrence intervals (the average times between gap-filling earthquakes) ranging from periods as short as 22 years, such as at Parkfield, to several thousands of years.

Since 1965, when the gap hypothesis was introduced, 17 major earthquakes have occurred within previously identified gaps. Although the locations and approximate magnitudes of these events were foretold, these successes were not true earthquake predictions in the sense that the times of occurrence were not stated reliably in advance. The existence of the gap does not in itself signify that an earthquake is imminent, only that the potential for one is higher than that in adjacent areas. The most recent large gap-filling earthquake was the magnitude 8.2 event on 19 September 1985 near Michoacan, Mexico, that resulted in about 10,000 deaths. The site was clearly identified and labelled in the scientific literature five years before.

The determination of the average rate of recurrence of strong earthquakes on a fault is an important element in long-term hazard assessment. Recorded history is short compared to the time scale of geological processes, especially in a country as young as the United States. Therefore, the recent development of techniques for extending the record of earthquakes on a fault into the more distant past by using geological evidence has been one of the major achievements of the research under the National Earthquake Hazards Reduction Program. These so-called paleoseimological methods have yielded, for example, the extension of the history of past major earthquakes on the San Andreas fault in southern California back about 2,000 years--during which time 12 major earthquakes occurred on this section of the fault. Although the scatter in the time intervals between major earthquakes makes it impossible to predict the time of the next one accurately on this basis, such recurrence data, supported by known rates of plate movements, make it possible to estimate the probability of recurrence at any time after a given event.

From this kind of analysis, a probability of 50 percent has been established for the occurrence of a great earthquake in the next 30 years on the San Andreas fault near Los Angeles. Similar analysis, taken by itself, has given a probability of 67 percent for a significant earthquake on the Parkfield segment of the fault by the spring of 1993. However, a physically reasonable model that incorporates the somewhat "off-schedule" Parkfield earthquake of 1934 (Figure 3) leads to a much higher probability for Parkfield within the next few years, and it is this calculation on which the current Parkfield prediction experiment is based.

Long-term predictions--on the time scale of decades--are important for planning hazard mitigation efforts, as well as for planning future scientific experiments. The accurate prediction of the time of occurrence on the scale of weeks to a few days or hours, on the other hand, requires the identification of specific anomalous precursory phenomena.

3.2 PROBLEMS OF SHORT-TERM EARTHQUAKE PREDICTION

The basic model of earthquakes that emerges from data on seismic gaps and plate tectonics theory is remarkably simple. Earthquakes are produced by sudden slippage on surfaces of failure ("faults") that relax elastic strains that have accumulated over long periods of time due to the relative movements of the earth's lithospheric plates. The direction and amount of slip are governed by the total strain accumulated across the fault between successive rupture events. Thus each earthquake terminates one cycle of strain accumulation and initiates the next.

The key question for short-term earthquake prediction is that of understanding the physical processes that determine the time during the strain-accumulation cycle at which failure occurs. Laboratory analogs of earthquakes and theoretical considerations permit several possibilities that need confirmation or refinement from field evidence. In some models, the time of failure may simply be set by the strain released in the previous earthquakes; the next event will occur when the strain drop recovers. Alternatively, the time of failure may be controlled by localized conditions surrounding the future point of rupture initiation (hypocenter of the earthquake) and thus may be sensitive to the history of movement on adjacent segments of the fault. The dynamic rupture (the earthquake itself) might initiate spontaneously once the threshold stress has been achieved, or it may begin after peak stress, if the fault-zone materials undergo strain softening. These multiple and contradictory hypotheses are all permitted, given the limitations of even the best available observational and laboratory data. We critically need measurements of the rheological behavior of the fault during the interval from the late stages of the strain accumulation cycle through release in the earthquake.

The role of variations in the distribution of physical properties in the fault zone (permeability, pore pressure, frictional strength, etc.) and in geometric irregularities in the fault plane (bends, kinks, steps, etc.) are also poorly understood, but they are clearly important for establishing where the earthquake will initiate as well as for estimating the eventual size of the rupture zone on which its magnitude depends.

At present, the most promising approaches to short-term prediction center on phenomena that have been observed before some, but not all, earthquakes. For example, many earthquakes are preceded by smaller shocks at or very near their hypocenters. While these foreshocks can at present be reliably differentiated from background seismicity only in retrospect, their occurrence suggests that localized, non-linear processes that lead to other precursors initiate the failure process in the hours to days before the principal dynamic rupture.

Direct detection of these precursory processes requires that measurements be made at very short range (a few kilometers) because the amplitude of the deformation signals decays inversely with the cube of the distance ($1/r^3$). Currently available strainmeters mounted on the earth's surface are limited by environmental noise and intrinsic instrumental instability that can be overcome only by placing them deep within the fault zone. In addition, measurements at the ground surface may not reflect the tectonically important deformations at the depth of the earthquake source--some 5 to 15 kilometers in, for example, the Parkfield area (see Figure 4).

Seismic waves generated by either micro-earthquakes or artificial sources are also an extremely important and powerful tool for probing the state of the fault zone because they are sensitive to changes in both elastic and anelastic properties of the medium. As with strain instrumentation, seismometers have adequate sensitivity, but they are limited in practice by the severe attenuation of high-frequency seismic waves that occurs near the earth's surface. Installation of seismometers at modest depths of about one kilometer would place them below the most severely attenuating layer, and this would permit us to extend the useful frequency band width from about five to ten octaves and would increase the sensitivity by a factor of about 100.

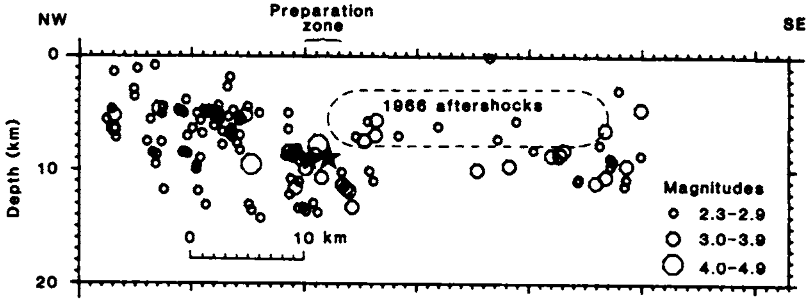

Figure 4: Cross section of seismicity for 1975-1984 along the length of the San Andreas fault in the Parkfield area, showing the distribution of earthquakes with depth. Relative focal depths are accurate to 1-2 km. For reference, the hypocenters of the immediate foreshock of M_L 5.1 and the main shock of 1966 are shown as the small and large stars, respectively, and the approximate 25-km-long outline of the 1966 aftershock zone (rupture zone) is dashed. From Bakun and Lindh (1985).

4. WHAT IS NEEDED TO CAPITALIZE ON THE PARKFIELD PREDICTION

The present program to predict the next Parkfield earthquake has necessarily focused on those measurements and instrumentation systems that are already available, can readily be deployed in the region, and are economically feasible under current circumstances. If, however, we are truly to understand the physics of the rupturing process and the manner in which damaging ground motions are propagated in the epicentral area, bold new techniques and instrumentation are called for. Following is a list of experiments and areas of investigation that are deemed particularly promising.

4.1 MEASUREMENTS OF PHYSICAL PARAMETERS AT DEPTH

All the current Parkfield instruments are located within a few hundred meters of the ground surface and thus respond most sensitively either to dramatic changes within the fault zone, as might occur during a significant earthquake (and apparently did in 1966), or to localized and shallow phenomena. They lack the sensitivity to physical processes occurring in the hypocentral zone of the predicted event--at depths of 5 to 15 kilometers--simply because of the $1/r^3$ decay of strain amplitude. Measurements made deep in the fault zone offer the best hope for overcoming the limitations of the present experiment and for directly addressing the fundamental issue itself.

A series of five boreholes drilled to a depth of about 5-kilometers is proposed herein to investigate material properties and the state of stress within the "preparation zone" around the predicted hypocenter, as well as elsewhere along the fault and in the adjacent crust external to the fault zone. No boreholes currently exist in the Parkfield area that are suitable for deepening, so new holes must be drilled. Multiple drill holes would greatly expand our knowledge of the role, if any, played by the contrast in material properties between those of well-developed fault zones and those of less-deformed adjacent crust in the generation of large earthquakes. In locating sites for boreholes, it should be noted that both earthquake hypocentral locations and focal mechanisms indicate that the San Andreas fault is essentially vertical to a depth of at least 15 km in the area, and all geologically recent displacements appear to have taken place along a single, relatively simple strand.

In each deep drill hole we will measure a suite of physical properties and sample the rocks and fluids encountered during drilling, in order to determine the crustal state within and adjacent to the fault zone. Specific measurements will include shear stress, fluid pressure, seismic wave velocity, temperature, fluid chemistry, rock composition, permeability, density, magnetic susceptibility, and remnant magnetization. Continuous measurement of formation fluid pressure and temperature will be made at the bottom of the hole and at shallower levels following completion of the sampling program. If the working range of borehole strainmeters can be extended, they will also be emplaced deep within each hole to complement the dilatational strain measurements from the pressure data. Seismometers will be installed at several levels in the hole to record both man-made surface sources and nearby micro-earthquakes. High-precision measurements of seismic waves will be used to monitor changing physical conditions at depth in the fault zone, including variations in wave velocity, anisotropy, and attenuation. The technology, including instruments and cables, available for borehole monitoring to a depth of 5 km has been evaluated by others as part of the background for other major initiatives in geological investigations of the crust based on deep drilling. The preliminary sketch of a science plan for an enhanced Parkfield experiment presented here draws freely on the conclusions of these evaluations. The suggested observations are judged to be feasible.

Deep drilling would also permit us to attack fundamental geological questions concerning the nature and level of interplate driving forces, the role of traction on the base of the plate in loading crustal faults, and the transition between brittle (earthquake-generating) and ductile (aseismic) behavior in the earth. The most efficient means for addressing these questions would be with a profile of stress and heat-flow measurements made in intermediate-depth (1 to 2 kilometers) drill holes extending transverse to the fault to a horizontal distance of about 15 kilometers. Such measurements, if made before and after the predicted Parkfield earthquake occurs, would provide the first direct measurement of the coseismic stress change, which would be invaluable for calibrating current procedures that depend strongly on idealized models of the rupture process. It is recognized that groundwater flow may make heat-flow measurements difficult in holes as shallow as 1 km, and this is a primary reason for needing some deeper holes as well.

Although geochemical sensors such as radon and hydrogen emanations from fault zones have not proved to be as effective as earthquake precursors as had once been hoped, the Parkfield prediction offers an opportunity for a definitive experiment in this field. Therefore we propose to instrument a number of the holes for geochemical monitoring, where feasible, in order to understand better the chemical as well as physical processes in and near the fault zone associated with the earthquake and the processes leading to it.

4.2 CRUSTAL INVESTIGATIONS

A detailed and accurate description of the earth's crust in the Parkfield region is a necessary first step in the meaningful analysis of the data to be collected during the initiative proposed herein. Such a structural model of the crust is required in several aspects of the program: locating earthquakes, calculating seismic-wave propagation, characterizing the buildup of strain on the fault, and selecting emplacement targets for deep borehole instruments. The simplified crustal-structure models for this region now in use are simply inadequate for the task of interpreting fully the new observations that will be forthcoming on earthquakes, seismic waves, and crustal deformation. Improvement of the models to the required levels of complexity and accuracy is an exercise in detailed three-dimensional imaging of the distribution of physical properties. Particularly important is the understanding of the geologic structure within the wide fault zone itself, and how physical properties change with depth and along the length and width of the zone. In turn, this information will allow numerical modelling of the strain buildup, detailed prediction of expected strong ground motions, and the precise locating of small earthquakes. Furthermore, experiments involving continuous monitoring of fault-zone properties by seismic, electrical, or other methods, will depend on detailed and accurate crustal models. This opportunity has already been recognized by the NSF-funded Program for Array Seismic Studies of the Continental Lithosphere (PASSCAL), which has specifically pointed to the Parkfield area as a target of opportunity.

A number of methods exist for acquiring the needed information, but seismic imaging techniques are probably best suited to the task. Conventional seismic reflection and refraction profiles provide two-dimensional views, although they are inadequate to define the somewhat chaotic structures at subkilometer scale that characterize the fault zone. Higher resolution may be obtained with three-dimensional reflection surveys. Probably the most accurate pictures will be obtained, however, through application of seismic tomography reconstructions based on data collected in densely spaced arrays of sensors on the ground surface and in deep boreholes. Both natural earthquakes and controlled articial sources can be used, and crosshole imaging will be possible from multiple deep boreholes. With these advanced seismological techniques, taken together with the deep drilling results themselves, we will be able for the first time to portray the inner makeup of a major active fault zone in some detail.

4.3 EXTENSION OF THE AREA OF OBSERVATION

The key element in the proposed new phase of the Parkfield experiment is the acquisition of data required as a base for great improvements in our understanding of the physics of the earthquake process. Although our models are based on the concept that energy release is localized along the fault and is controlled by the mechanical properties of the fault zone and the close-in stress state, we know that the loading process is regional in extent. There is evidence that some premonitory phenomena may appear away from the immediate vicinity of the fault, perhaps at considerable distance. An adequate database for studying earthquake physics must, therefore, include observations in this "far-field" region. In addition to the enhanced observations near the fault proposed herein, stations for monitoring strain accumulation and release in the broader, nearby region will be established in a coarser network, distributed out to distances of at least 30 kilometers. Strainmeters in 300-meter boreholes and wells in which water levels can be measured will be the primary tools. These should be tied together by high-precision geodetic surveys, to be repeated at least semiannually if the time before the earthquake proves to be sufficient.

In addition to the need for more far-field monitoring, a special need exists to extend the detailed monitoring farther southeast along the fault than currently is the case. Although the prediction on which the Parkfield experiment is based calls for a rupture event limited to the 25-kilometer-long segment which has apparently broken in the past five Parkfield earthquakes, there is also great interest in the behavior of the adjacent fault segment extending some 40 km farther southeast. This portion of the fault last broke in the great 1857 earthquake of about magnitude 8, although with significantly smaller slip than that associated with the additional 250 km of rupture still farther southeast at that time. Thus the strain released in 1857 is now restored along this 40-km segment, resulting in a high-probability seismic gap, whereas it may take another 200 years for the strain to reach the same level farther southeast. There is a real possibility that the predicted Parkfield earthquake will break through into this 40-km segment of the fault, causing an earthquake of about magnitude 7 rather than magnitude 6, and affecting some 175,000 people.

A fundamental question of earthquake mechanics is how the tectonic loading is shifted to adjacent fault segments when one portion breaks. As part of the initiative proposed herein, at least the basic observations being made in the Parkfield segment will be extended into this southeastern segment. The most important need is for data that will reveal the immediate and short-term effects on this segment, whether or not the rupture actually extends through it. A two-color laser electronic distance measurement station, several strainmeters and creepmeters, and a modest extension of the dense seismographic network into this area will provide the required data. In-situ stress measurements at a few points, both before and after the Parkfield earthquake, are also essential.

If the predicted earthquake does in fact "run away" to create a major earthquake, the data that will have been gathered will be an invaluable addition to earthquake-prediction efforts. Great earthquakes are known to be complex events, characterized by momentary pauses in the propagation of the rupture. It is not known how possible precursory phenomena might be distributed in space or time, or the details of how the rupture moves through barriers along the fault. Although the proposed expansion of the Parkfield observations is not adequate to provide all the details of these complex processes, it will produce by far the best data set ever collected.

4.4 STRONG-MOTION ARRAYS

Primarily for engineering studies, an array of instruments to record strong ground motion operated by the state of California is already installed in the Parkfield area, comprising 46 three-component instruments at intervals of two to three kilometers. These instruments will provide an excellent description of the general character of strong ground shaking when the preicted earthquake occurs. However, an additional important opportunity exists to measure the ground motion in dense arrays in which the spacing of instruments is on the order of 100 meters (100 meters approximates the half-wavelength of seismic energy at about 2 hz, which is typical of damaging earthquake frequencies). The data from the dense arrays are needed in the earthquake-resistant design of major bridges, tunnels, piers, and other extended structures where the spatial coherence of ground shaking is an important engineering issue. The arrays will be particularly useful if they include instruments in boreholes as well as surface installations. For engineering purposes, the best location for any array is near the fault, where the strongest shaking is expected. The same arrays used to measure the spatial variation of strong ground shaking can also be used to resolve the details of energy release during rupture of the nearby portions of the fault. Thus, the potential exists at Parkfield to observe and resolve the earthquake rupture process to an unprecedented degree.

4.5 SPECIAL MEASUREMENTS OF STRUCTURAL RESPONSE

A predicted earthquake offers the unique opportunity to engineers to thoroughly instrument specific structures in order to measure their behavior during the event. However, there are no major buildings or structures in the expected area of strong shaking during the predicted Parkfield earthquake, so the obvious choice of instrumenting multi-story buildings, freeway bridges, etc. is simply not a possibility. What could be done, however, is to make a careful survey of the area to determine whether there are small structures, such as one-story unreinforced masonry buildings, small bridges, storage tanks, or buried pipelines, that could be instrumented to yield useful engineering results. For example, a carefully instrumented unreinforced brick building could produce results helpful in assessing the tremendous risk posed to such structures by earthquakes in our major cities. Major engineering structures could, of course, be built in the Parkfield area solely for use as experiments, but time and expense, in addition to the fact that the predicted event will probably not be large by the standards used to measure potentially destructive earthquakes, argue against this approach.

One engineering experiment might, however, be both practical and significant. Very little experimental data exist on the earthquake response of buried structures, and their behavior is of considerable engineering interest. For example, a buried steel pipeline, L-shaped in plan, and large enough in diameter to permit work inside the pipe, could be installed as an experiment. One leg of the L could cross the fault to observe details of how ductile pipelines react to fault rupture. The other leg could be parallel to the fault, at some distance, and could be used to investigate the relations among free-field ground motions, strains in the pipe, and stresses in the soil. A man-hole and junction-box at the joint of the L could yield valuable information concerning the earthquake response of more massive buried structures. Other experiments on this scale could also be developed.

4.6 EXPERIMENTS IN SOIL MECHANICS

A small experiment is currently planned for Parkfield to study the problem of soil liquefaction which occurs during strong ground shaking. It appears possible to expand the scope of this experiment significantly and to provide much-needed field data concerning this important phenomenon. Liquefaction of soil deposits during earthquakes not only causes extensive direct damage to structures by loss of foundation strength, but also is the initiating mechanism for most earthquake-triggered landslides, excepting rockfalls. These experiments would employ strong-motion accelerometers, piezometers, deformation gauges, and other instrumentation to measure the strain in the soil, the development of excess pore pressure, and, finally, the virtually complete loss of strength as the soil liquefies.

5. BROADER SIGNIFICANCE OF THE PARKFIELD INITIATIVE

The increased knowledge of earthquake processes to be gained by means of a carefully designed research program at Parkfield will certainly be applicable to other sites along the San Andreas fault, as well as to faults in other geological regimes. Indeed, it is this transferability of knowledge that is the primary argument in support of the Parkfield initiative proposed herein. Three specific segments of the San Andreas fault system in southern California have been identified as having a high probability of a major earthquake within the next 30 years (including the unlabelled San Jacinto fault on Figure 2), but no specific predictions have been made comparable to the one at Parkfield. Plans for increased monitoring of some of these sites have been initiated, and success in the Parkfield prediction will clearly make possible much better experimental designs at the other locations. Populations living close to each of the three southern California sites comprise literally millions of people, vastly greater than at Parkfield, and the social significance of reliable earthquake predictions in these southern areas could be profound.

It is the opportunity to acquire, for the first time, measurements of the relevant parameters within the region of the fault break and the region of strong ground shaking that makes the Parkfield initiative so important. Constraints of theoretical and numerical models of fault rupture based on adequate measurements will advance fundamental understanding of earthquake physics. One of the results of the Parkfield research should be a determination of the extent to which the Parkfield segment is unique, as we know it is in some ways, rather than characteristic of other longer segments of the San Andreas fault. Even though the regularity of occurrence of the events may not be so obvious at other places, the basic physics of elastic energy accumulation, stress concentration, and fault rupture should be seen elsewhere as well.

The energy budget of an earthquake is poorly known. Qualitatively, it is known that the strain energy released is distributed among several phenomena such as the fresh fracture surface created, heat in the rocks along the fault surface, redistributed mass, and radiated semismic waves. But the quantitative distribution into these forms is not known. The proposed subsurface observations within the source volume of the impending Parkfield earthquake, including measurements of stress and temperature changes, will yield for the first time the hard data that are needed to put bounds on these values. Other key questions, such as the magnitude dependence of the energy distribution, will not be resolved by a single experiment, but the contribution to the understanding of earthquake dynamics will be great indeed.

6. THE RESEARCH TEAM

As one of the principal federal agencies in the earthquake-hazard reduction program, the U. S. Geological Survey is playing the leadership role in the Parkfield prediction experiment. However, many other players are also involved, not only through direct independent funding, such as in the case of the California Division of Mines and Geology and the Electric Power Research Institute, but also through the Geological Survey's external grants program. The current Parkfield experiment has been specifically identified in the Geological Survey's requests for research proposals, and university and industry participation currently exists and is being further encouraged. Under the greatly expanded intiative proposed herein, we anticipate wide participation by the scientific community, perhaps involving a broadly representative high-level advisory and planning body.

7. INTERNATIONAL ASPECTS

Because the Parkfield situation is at this time unique in the world, international attention has focused on scientific activities here as had been expected. In this light, international participation is being encouraged insofar as it is practical. For example, Chinese scientific participation has been specifically invited in the December 1985 review of the protocol between the U.S. Geological Survey and the State Seismological Bureau of China. And appropriate foreign experiments have been sought, such as that of an Australian scientist using a novel three-component down-hole strain-measuring device. The Parkfield opportunity is unique, but the application of the Parkfield results to earthquake prediction is global in extent and is of potential benefit to millions of people exposed to earthquake hazards.

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